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Original Research Report

Response-Conflict Moderates the Cognitive Control of Episodic and Contextual Load in Older Adults

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Abstract

Objectives: Decline in cognitive control is one of the primary cognitive changes in normal aging. Reaching a consensus regarding the nature of these age-related changes, however, is complicated by the complexity of cognitive control as a construct.

Methods: Healthy older and younger adults participated in a multifactorial test of cognitive control. Within participants, the procedure varied as a function of the amount contextual load, episodic load, and response-conflict load present.

Results: We found that older adults showed impaired performance relative to younger adults. We also found, however, that the response selection process underlying the response-conflict manipulation was a major moderator of age-related differences in both the contextual and episodic load conditions—suggesting a hierarchical organization.

Discussion: These findings are consistent with previous findings, suggesting that deficits in cognitive control in older adults are directly related to the resolution of response-conflict and that other apparent deficits may be derivative upon the more basic response-conflict related deficit.

Keywords: Cognition—Cognitive control—Executive function—Memory—Stimulus-response association—Task-switching

Decline in cognitive control, the processes that organize, integrate, and modify perceptual, motor, and cognitive acts, is one of the primary cognitive changes in normal aging (Drag & Bieliauskas, 2010). Because cognitive control involves the coordination and organization of behavior on the basis of internal plans and goals and subserves higher order processes such as planning and reasoning, these age-related changes can result in performance problems on a multitude of tasks and therefore significantly impair day-to-day function. Reaching a consensus regarding the nature of these age-related changes, however, is complicated by the complexity of cognitive control as a construct (Gopher, 1996; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Posner & DiGirolamo, 1998). Cognitive control may be required across a range of levels and types of processing. For example, inhibiting distracting stimuli in the environment versus choosing an appropriate motor response from among alternatives or intentionally memorizing surrounding contextual information and later recalling particular aspects of it are all actions that require cognitive control. Distinct signals are likely to be involved in controlling the selection of appropriate stimulus–response associations with respect to each of these quite different levels of processing. Teasing apart the architecture of cognitive control, and how it is affected by aging, is thus an important endeavor.

Koechlin, Ody, and Kouneiher (2003) recently proposed a modular model in younger adults for the cognitive control of contextual ("signals related to the immediate context in which the stimulus occurs") and episodic ("signals for guiding action selection which are attributable to a past event instigating a temporal 'episode' in which a new set of rules apply") information with varying levels of demand (Koechlin & Summerfield, 2007, pp.1–2). Their model forwards that these functions are nested hierarchically, with functionally dissociable representations within the lateral prefrontal cortex (LPFC), such that each level of the LPFC mediates the processing of a distinct signal (Chambon, et al., 2008). These signals increase in "temporal scale" along the antero–posterior frontal axis. For example, the control signals that mediate the immediate context in which a stimulus occurs originate in caudal regions, whereas processes that tap more distant events or events related to past events (episodic) rely upon rostral areas of the LPFC.

Age-related shifts in the magnitude of neural responses in the LPFC have been well documented, including in the specific areas found to be involved in these different types of cognitive control by Koechlin and colleagues (2003) (e.g., Brodmann's areas 9, 44, 45, and 46; Logan, Sanders, Snyder, Morris, & Buckner 2002). Alterations in neural responses in these areas are likely to be involved in age-related cognitive decline according to a number of theories of aging (Braver & Barch, 2002; Buckner, 2004; Moscovitch & Winocur, 1995; Raz, Gunning-Dixon, Head, Dupuis, & Acker 1998; West, 1996), and age-related atrophy in these regions may mediate individual differences in age-related cognitive decline (Steffener, Reuben, Rakitin, & Stern, 2011). Furthermore, it is plausible that the pattern of decline in aging may reflect the hierarchical organization proposed by Koechlin and colleagues.

To systematically investigate the effects of different cognitive control processes that are affected by aging, we implemented a version of Koechlin and colleagues' (2003) task-switching paradigm. In this protocol, participants are presented with uppercase and lowercase vowels and consonant letter stimuli and make either a left or a right hand key press discrimination about the stimuli that is cued by the letter's color. Context was manipulated as a function of the number of tasks that the participant had to perform within each block of the experiment: In low (single task) contextual load blocks, participants made either only vowel/consonant discriminations (Task A) or only lowercase/uppercase discriminations (Task B), whereas in high (dual task) contextual load blocks, participants switched between the two types of discriminations, performing Task A and Task B within the same block of trials (e.g., [AABABBAB]). These blocks have a high contextual load in the sense that participants must actively switch between the two tasks, depending on the color of the stimulus. Figure 1 shows trials in a high contextual load (and low episodic load), block.

A recent meta-analyses indicated a strong effect of aging on task-switching performance costs (Verhaeghen, 2011; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). These effects may reflect the costs of setting up and maintaining multiple task set decision rules, and managing this added load in working memory, and are in this way comparable in mechanism to tasks of divided attention (Verhaeghen, 2011). Although age differences in performance costs may also be

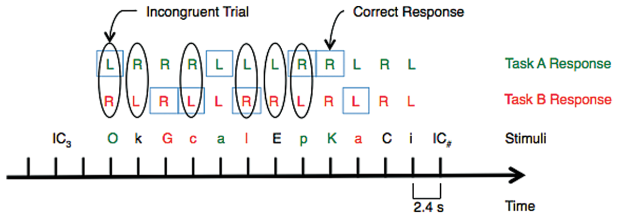

Figure 1. Time line of the events in a high contextual load (dual task), low episodic load (fixed color) block. Blocks of this type correspond to block types 3 and 4 in Figure 2. Example stimuli are immediately above the time line. No-go stimuli are colored black (for clarity) not white as in the actual task. Above that are the appropriate responses for vowel/consonant decisions (Task A) and lowercase/uppercase decisions (Task B), given the stimulus below. The correct response is indicated by a blue square. Incongruent trials are defined as trials in which the stimulus indicates opposing responses for Task A and Task B, and are indicated by ovals. Note the conunterbalancing of the number of trials for each task and congruency level. IC = instruction cue; L = left hand response; R = right hand response.

related to general cognitive speed and other individual differences (Kray & Lindenberger, 2000; Salthouse, Fristoe, McGuthry, & Hambrick, 1998), they cannot be entirely accounted for by other mechanisms. Other features of the current experiment, including the use of stochastic switching and multiple tasks, also increase performance costs in older populations (Kray, Li, & Lindenberger, 2002; Van Asselen & Ridderinkhof, 2000).

Having to remember which task each stimuli color referred to within each block was a second variable, referred to as the *episodic load* manipulation. In low load episodic blocks, letters always appeared in red or green, and green letters always serve as a cue to perform Task A and red letters always serve as a cue to perform Task B. Thus, the stimuli-color mapping to task was fixed in all of the low episodic load conditions, across blocks. In high load episodic blocks, on the other hand, the mapping between task and stimuli-color varied across blocks such that in some blocks, one color (e.g., yellow) cued Task A, whereas in another block, yellow cued Task B.

Cognitive control is necessary in the episodic load manipulation because participants are forced to mediate conflicts among similar, but not identical instruction sets across blocks. That is, they must update the color-to-task rule. In this case, blocks are considered separate temporal episodes, akin to the distinction between learning episodes commonly made in the memory literature (Tulving, 1989). However, the between-block demands are due to the active maintenance of block-specific task instructions within the episodic buffer, a limited capacity cognitively controlled component of working memory that is "assumed to play an important role in feeding information into and retrieving information from episodic long term memory" (Baddeley, p. 421), rather than in the sensory-specific buffers that maintain item information within a block (Baddeley, 2000). According to Baddeley, phenomenon such as articulatory suppression of visual serial learning tap this component

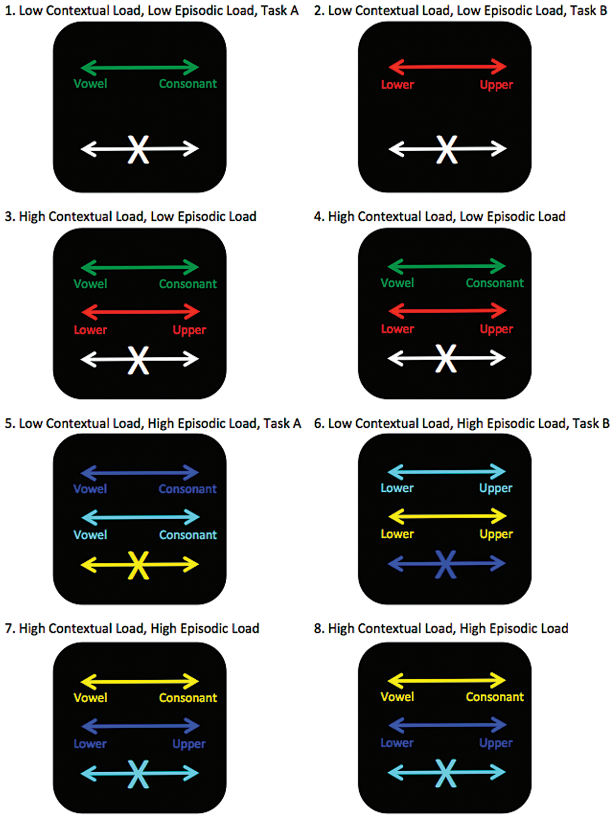

Figure 2. Instruction cues for the eight blocks, presented here in an order that allows easy comparison among the conditions, not the actual order of testing. Note that the eight blocks only include six unique conditions: Blocks 3 and 4 are identical and Blocks 7 and 8 are identical. The doubling of the high episodic load (i.e. dual task blocks) was necessary to equate the number of vowel/consonant decisions and lowercase/upper case decisions across the low and high contextual load conditions. The direction of the arrow indicates the correct hand press (left or right).

of working memory. Studies of the effect of aging on this phenomenon are scant, but at least one study suggests that the effects of aging on recognition memory is unrelated to articulatory suppression (Verhaeghen, Vandenbroucke, & Dierckx, 1998), suggesting age invariance. A study assessing the functioning of the episodic buffer in children with and without intellectual disabilities, however, reported that this function tracks with mental age (Henry, 2010). However, no study to our knowledge has directly compared healthy older and younger adults on this function (but see Germano, Kinsella, Storey, Ong, & Ames, 2008, for a study that suggests dysfunction in the episodic buffer component of cognitively controlled working memory [as indexed by the ability to strategically integrate and organize information through chunking] with increasing neurodegenerative disease). Nonetheless, Koechlin's conception of episodic load, as operationalized in the current task, is rather unique, and we are currently unaware of any attempts to understand the effects of aging on episodic executive demands so defined.

Koechlin and colleagues' (2003) study design also included a third variable, called the response-conflict manipulation, although the behavioral and imaging data relevant to this manipulation were not reported. Low response-conflict occurs when the correct key press for vowel/consonant (Task A) and lowercase/uppercase (Task B) decisions are the same, whereas high response-conflict is a result of the correct key press for Task A being different from the correct key press for Task B. This is because, as each letter stimulus is either uppercased or lowercased, and is either a vowel or a consonant, each stimulus potentially informs both task discriminations; only the color of the stimulus serves as a cue for which specific discrimination should be made on each trial. Thus, it is possible that a single stimulus may indicate either congruent (when the response for Task A and Task B requires the same key press, e.g., a green "e" and a red "e" both require left hand button presses) or incongruent (when the response for Task A and Task B require opposing key presses; e.g., a green "E" requires a left hand button press, but a red "E" requires a right hand button press) responses for the two stimulus dimensions.

Sudevan and Taylor (1987) were the first to report that congruent trials produce quicker (and more accurate) responses than do incongruent trials within task-switching paradigms. Since then, this phenomenon, called the task–rule congruency effect (TRCE), has proven to be robust. TRCE has been shown to reflect prefrontal functioning in at least two studies. Both Konishi, Chikazoe, Jimura, Asari, and Miyashita (2005) and Konishi, Jimura, Asari, and Miyashita (2003) found increased activation in prefrontal areas for incongruent relative to congruent trials using functional MRI in a modified Wisconsin Card Sorting Test, a test which may tap the same mechanisms as the response-conflict manipulation in the current design. The effect has also been shown to be larger in a number of different populations in which the prefrontal cortex is either less developed or functionally compromised, including monkeys (Stoet & Snyder, 2003), children (Cepeda, Kramer, & Gonzalez de Sather, 2001), children with attention deficits (Cepeda, Cepeda, & Kramer, 2000) and, according to a study by Meiran, Gotler and Perlman (2001), healthy older adults, in which the TRCE effect size ranged from $\eta^2 = 0.14$–0.18.

The goal of the present study was to simultaneously examine these three different types of cognitive control (contextual, episodic, and response-conflict) at different levels of load in older and younger adults and to gauge differences between younger and older participants on these components independently, and in interaction. Our primary interest was determining whether one or more of these forms of cognitive control is especially impacted by age, and whether there are interactions between the level of cognitive control and age group that would suggest that one or more of these demands moderate the effects on performance of the others.

Method

Participants

Participants were 25 healthy younger adults and 25 healthy older adults, recruited using established market mailing procedures. One younger and one older adult averaged less than 50% accuracy on incongruent trials across conditions, and so their data were excluded from analyses according to previous reports assessing similar effects (Kessler & Meiran, 2010). All participants were screened for current neurological or psychiatric diagnoses and medication use. Older adults were screened for dementia via the Dementia Rating Scale (Mattis, 1988). IQ approximation was obtained with the Wechsler Test of Adult Reading (The Psychological Corporation, 2001). Informed consent, as approved by the Internal Review Board of the College of Physicians and Surgeons of Columbia University, was obtained prior to study participation. Participants were paid $25. Table 1 provides a demographic and neuropsychological assessment ratings of the participants.

Apparatus

Testing was conducted on an Apple Macintosh G4 iBook with a 12" LCD color monitor in a dedicated testing room. Responses were made on the keyboard by pressing either the "*z*" or "/" key with the index fingers of both hands. This apparatus yielded a maximum response time acquisition accuracy of ±8 ms. Stimuli were presented on the color monitor and, for practice trials, through the built-in speaker. Participants adjusted the speaker volume to a comfortable level, and no participant reported that difficulty hearing the stimuli affected their performance. Stimulus presentation and response acquisition were driven by the Psyscope X experimental design package, version B53 (Cohen, MacWhinney, Flatt, & Provost, 1993).

Tasks

The experimental procedure was modeled directly after Koechlin and colleagues (2003) "task" experiment. The basic block included an instruction cue followed by 12-letter stimuli, pseudorandomly chosen from the set {A, E, I, O, a, e, i, o, C, G, K, P, c, g, k, p}. The time line of a sample (high contextual load, low episodic load) block is illustrated in Figure 1. In all blocks, task trials (where participants were supposed to make a response) constituted two thirds of the trials and no-go trials (where the correct action was to withhold a response) constituted one third of trials. No-go trials were necessary in the design to create the high episodic load manipulation, which required three variable colors (results of data from the no-go trials were not of primary interest and are not reported here). Stimuli were presented in either two (red and white or green and white) or three (red, green, and white or cyan, yellow, and blue) colors, depending on the block. The block and color determined whether participants were instructed to (1) make a vowel/consonant decision (Task A), (2) make a lowercase/uppercase decision (Task B), or (3) withhold a response.

Three variables, each containing two levels of load, were manipulated. Contextual load was manipulated as a function of the number of tasks in each block. In low contextual load blocks, participants completed only one task, whereas in high contextual load blocks, participants completed two tasks and had to actively switch between the two tasks. Contextual load is a variant of the many available task-switching assessments. Because an intrinsic characteristic of the stimulus (i.e., its color) cues participants about which of the two tasks they should perform, rather than a memorized pattern, the current manipulation is dissimilar from the paradigmatic version developed by Rogers and Monsell (1995). The current version employed stochastic (Monsell, Sumner, & Waters, 2003) as opposed to patterned switching, so that from trial-to-trial, expectancy of a switch between tasks was reduced. Task-switching paradigms produce two different kinds of performance costs: switch costs (the performance difference between switch and nonswitch trials within dual task blocks) and mixing costs (the average difference in performance between single task and dual task blocks [e.g., Kray & Lindenberger, 2000]). Because the within-participants factorial crossings of the cognitive control load manipulations greatly reduced the number of trials available for within-block comparison needed to measure switch costs, our focus here was on mixing costs.

Episodic load was manipulated as a function of the mapping of stimuli color-to-task. In low episodic load blocks, the color-to-task mapping was fixed. In these blocks, letters appeared in green, red, and white. A green letter always served as a cue to perform Task A, red letters always served as a cue to perform Task B, and white letters always indicated a no-go trial. In high episodic load blocks, stimuli always appeared in one of the three colors, blue, cyan, or yellow. In these blocks, the mapping of color-to-task varied. For example, in one block, yellow might serve as a cue to perform Task A, but in another block, yellow might serve as a cue to perform Task B.

Finally, response-conflict load was manipulated on a trial-by-trial basis. In low response-conflict (congruent) trials, stimuli corresponded to either a right hand response on both tasks (i.e., uppercase consonants) or a left hand

Table 1. Description of the Participants

Variable	Older adults	Younger adults
N	24	24
Age (years)	69.4 ± 4.5	24.2 ± 3.3
Age range	63–84	19–32
% Female	67	46
Education (years)	16.9 ± 2.9	15.3 ± 1.9
DRS total	141.5 ± 2.2	141.3 ± 2.4
WTAR Raw Score	41.3 ± 7.7	37.8 ± 9.3

Note: DRS = Dementia Rating Scale; WTAR = Wechsler Test of Adult Reading. Values are means ± *SD*, except for *N*, age range, and % Female.

response on both tasks (i.e., lowercase vowels). Thus, the correct key press for Tasks A and B were the same. In high response-conflict (incongruent) load trials, stimuli features indicated different hand responses (i.e., uppercase vowels and lowercase consonants), thus the correct key press differed for Tasks A and B.

In all blocks, stimuli were counterbalanced so that (1) no more than two task or no-go trials occurred in a row; (2) the crossings of color, case, and vowel/consonant identity were equally likely; (3) no more than two vowel/consonant or uppercase/lowercase decision trials occurred in a row; and (4), and congruent and incongruent trials were equally likely and repeated no more than two successive trials.

Procedure

Participants completed eight types of task blocks (illustrated in Figure 2), each presented 8 times in an 8 × 8 balanced Latin square design. Two rounds of training were completed before testing began. In the first phase of training, a minimum of two and a maximum of four rows were presented, at the participant's request. The order of the blocks within the rows was selected at random from among the eight rows comprising the complete balanced Latin square that determined the order of block presentations within the testing phase. The instruction cue was left on the screen until dismissed by the participant. Each letter stimulus was presented for 2.4 s, during which the participant made a response. Trials were separated by a fixed 1.0-s intertrial interval (ITI). Feedback consisted of a tone presented immediately after an incorrect response. In the second phase of training, the selection of blocks was the same as for the first phase of training, and the instruction cue was presented for 2.0 s, followed by a 1.4-s ITI. Each letter stimulus was presented for 0.5 s, and there was a 1.9-s ITI. Responses were accepted during both the stimulus presentation and subsequent ITI. Feedback consisted of a tone presented after an incorrect response. The trial dynamics for experimental testing were the same as for the second training phase except that no feedback was given. The experimental procedure lasted approximately 1.5 hr. Only the data from the testing phase are reported below.

Results

Initial analyses indicated that the Latin square factors did not significantly interact with the effects of interest. These effects and their interactions were therefore dropped from all models, and the results presented are from the reduced models.

We began by attempting to replicate Koechlin and colleagues' (2003) reaction time (RT) results in the young adult group. They reported two main effects (of Contextual load and Episodic load) but no interaction. Vowel/consonant decision and lowercase/uppercase decision trials were combined so that the 64 blocks were divided into four conditions (two levels of Contextual load: low [single task] and high [dual task], crossed with two levels of Episodic load: low [fixed color] and high [variable color]) with 16 blocks each. A factorial analysis of variance (ANOVA) of mean RT for correct task trials for the younger adults in our sample that crossed Contextual load (low vs high) and Episodic load (low vs high) revealed a significant main effect of Contextual load ($F(1,23) = 116.4$, $p < .001$, $\eta_p^2 = 0.84$), such that RT was faster in the low versus high load blocks, and Episodic load ($F(1,23) = 89.43$, $p < .001$, $\eta_p^2 = 0.79$), such that RT was faster in the low versus high load blocks. However, contrary to the results of Koechlin and colleagues (2003), we also found a significant interaction between Contextual and Episodic load ($F(1,23) = 49.63$, $p < .001$, $\eta_p^2 = 0.68$). This interaction stemmed from a greater difference between low and high episodic load blocks in the high compared with low contextual load blocks.

Koechlin and colleagues (2003) reported that "in all conditions, the participant's error rates were lower than 3%" (p. 1182). In our sample, younger adults' accuracy averaged 93% (7% error rate) and ranged from 75% to 99%. The failure to replicate thus may be due to highly variable accuracy performance. This wider range in accuracy makes RT differences difficult, and perhaps impossible, to interpret. Thus, given that our sample did not perform in a homogenous manner and was not at ceiling, as was the case in Koechlin and colleagues (2003), we performed the analogous analysis using accuracy. A factorial ANOVA of accuracy (Number correct responses/Number correct responses + Number incorrect responses) for younger adults that crossed contextual and episodic load revealed a marginally significant main effect of Contextual load ($F(1,23) = 3.10$, $p = .09$, $\eta_p^2 = 0.12$), such that accuracy was higher in low as opposed to high load blocks, and a significant effect of Episodic load ($F(1,23) = 9.67$, $p = .005$, $\eta_p^2 = 0.29$), such that accuracy was higher in low as opposed to high load blocks. The interaction between Episodic and Contextual load was not significant ($F(1,23) = 1.85$, ns). This pattern of results replicates that found by Koechlin (2003) using accuracy-controlled mean RT and suggests that accuracy is a more sensitive measure of cognitive control than RT in the current study. For this reason, the remaining analyses will focus on accuracy measures.

Koechlin and colleagues' (2003) original design, after which the current task was directly modeled, included a Response-conflict load (low [congruent] vs high [incongruent]) manipulation, although data from the manipulation were not reported in the original source. Along with adding age group as a between-subjects factor, we also incorporated the Response-conflict load variable into the model. Within each block there were four congruent task trials and four incongruent task trials, for a total of 64 trials within each cell of the 2 × 2 × 2 within-subject factorial design. Results from a factorial ANOVA that crossed three within-participant factors, Episodic load, Contextual load, and Response-conflict load (low vs high), with one between-participants factor, Age group (younger vs older) revealed main effects for Contextual load ($F(1,46) = 21.67$, $p < .001$, $\eta_p^2 = 0.32$), Episodic load ($F(1,46) = 47.24$, $p < .001$, $\eta_p^2 = 0.51$), Response-conflict load ($F(1,46) = 131.52$, $p < .001$, $\eta_p^2 = 0.74$), and Age group ($F(1,46) = 12.71$, $p < .001$, $\eta_p^2 = 0.22$), in the expected directions. Accuracy was greater in the low load blocks relative to the high load blocks for each manipulation (Contextual, Episodic, and Response-conflict loads), and younger adults performed better than older adults on average.

Although interesting, these effects do not directly address the question of whether older adults show impairment in processing one or more types of cognitive control manipulations. Information regarding this question is found in the interaction terms of the ANOVA model. Each of the two-way interactions was significant: the interactions between Contextual load and Age group ($F(1,46) = 6.57$, $p = .01$, $\eta_p^2 = 0.13$), Episodic load and Age group ($F(1,46) = 8.07$, $p = .01$, $\eta_p^2 = 0.15$), and Response-conflict load and Age group ($F(1,46) = 20.03$, $p < .001$, $\eta_p^2 = 0.30$) were all significant, as were the interactions between Contextual and Episodic loads ($F(1,46) = 7.72$, $p = .01$, $\eta_p^2 = 0.14$), Contextual load and Response-conflict load ($F(1,46) = 23.05$, $p < .001$, $\eta_p^2 = 0.33$), and Episodic load and Response-conflict ($F(1,46) = 13.88$, $p < .001$, $\eta_p^2 = 0.23$). However, these interactions were qualified by significant three-way interactions. The three-way interaction between Contextual load × Episodic load × Response-conflict load was significant ($F(1,46) = 14.61$, $p < .001$, $\eta_p^2 = 0.24$) but of greater importance was the finding of three-way interactions of age group with (1) Contextual load × response-conflict load ($F(1,46) = 14.74$, $p < .001$, $\eta_p^2 = 0.24$) and (2) Episodic load × Response-conflict load ($F(1,46) = 13.82$, $p < .001$, $\eta_p^2 = 0.23$). These effects are illustrated in Figure 3. Neither the three-way interaction between Age group × Contextual load × Episodic load nor the four-way interaction between Age group × Contextual load × Episodic load × Response-conflict load was significant ($F(1,46) = 1.02$ and 0.12 respectively, ns).

The Age group × Contextual load × Response-conflict load interaction effect (Figure 3A) indicates that older adults' accuracy is especially impaired in dual-task blocks when the stimulus indicates different responses for the two tasks, that is, on incongruent trials. This interpretation is supported by post hoc simple effects analysis indicating a significant Contextual load × Response-conflict load interaction for the older adults ($F(1,23) = 17.80$, $p < 0.001$, $\eta_p^2 = 0.44$) and a nonsignificant Contextual load × Response-conflict load interaction for the younger adults ($F(1,23) = 0.02$, ns).

The Age × Episodic load × Response-conflict load interaction effect (Figure 3B) indicates that the effect of high episodic load (variable color-to-task mapping) affects the accuracy of the older adults more than the younger adults when the stimulus indicates different responses for Task A and Task B (e.g., on incongruent trials). This interpretation is also supported by post hoc simple effects analysis indicating a significant Episodic load × Response-conflict load interaction for the older adults ($F(1,23) = 29.68$, $p < 0.001$, $\eta_p^2 = 0.56$) but not for the younger adults ($F(1,23) = 0.76$, ns).

For completeness, we also performed an ANOVA on the task trial nonresponse rate. All four main effects produced significant changes to percentage of nonresponses in the expected directions. That is, the nonresponse rate was lower in the (1) low contextual load blocks versus high contextual load blocks ($F(1,46) = 21.33$, $p < 0.001$, $\eta_p^2 = 0.32$), (2) low episodic load blocks versus high episodic load blocks ($F(1,46) = 63.12$, $p < 0.001$, $\eta_p^2 = 0.58$), (3) congruent trials compared with incongruent trials ($F(1,46) = 7.18$, $p = 0.01$, $\eta_p^2 = 0.14$), and (4) for younger adults versus older adults ($F(1,46) = 4.53$, $p = 0.04$, $\eta_p^2 = 0.09$). Unlike the accuracy measure, tests of the effects of the interaction terms on nonresponse rate produced no significant effects, with the exception of the marginal interactions between Age group × Response-conflict load ($F(1,46) = 3.68$, $p = 0.06$, $\eta_p^2 = 0.07$) and Age group × Episodic load ($F(1,46) = 3.77$, $p = 0.06$, $\eta_p^2 = 0.08$). Thus, this variable is largely uninformative about age-related changes in cognitive control, apart from the finding (of a main effect of age group) that the older adults responded significantly less often than the younger participants overall.

Discussion

The current experiment examined age-group differences under conditions of varying cognitive control demands. Koechlin and colleagues (2003) proposed that contextual and episodic loads differ in temporal scale and affect different aspects of the LPFC in a hierarchical manner, a finding indicative of separate underlying cognitive processes for these two forms of cognitive control. We replicated Koechlin and colleagues' (2003) observations in our young group, albeit with accuracy as opposed to RT. In addition, we found age-related cognitive control dysfunction in the face of these different types of cognitive loads. These interactions between the level of cognitive control and age group may be especially informative because they allow inferences as to whether age-related differences in one function moderate age-related decline in the others.

The clearest evidence for differential effects of cognitive control demand on the older adults comes from the two three-way interactions affecting accuracy. The first is an interaction of Age group × Contextual load × Response-conflict load. As was mentioned earlier, high contextual load refers to dual task blocks, where participants must actively switch from performing Task A to performing Task B within a block. As such, the contextual load effect is equivalent to an accuracy difference between single task and dual task blocks—an effect synonymous with mixing costs (Monsell, 2003). The two-way interaction between Age group × Contextual load indicates that task switching

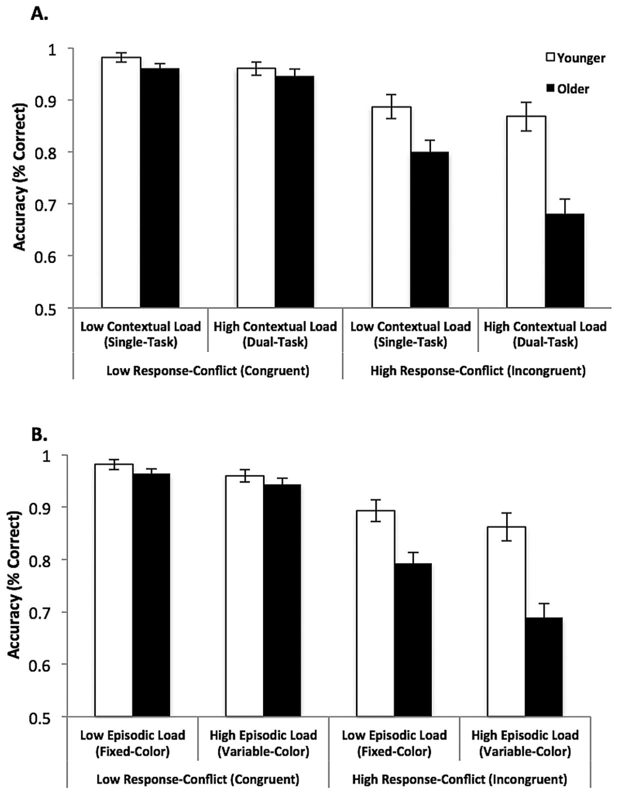

Figure 3. Results. (A) Significant Contextual load (low [single task] vs high (dual task)) × Response-conflict load (low [congruent] vs high [incongruent]) ×Age group (younger [white bars] vs older [black bars]) interaction. (B) Significant episodic load (low [fixed color to task mapping] vs high [variable color to task mapping]) × Response-conflict load (low [congruent] vs high [incongruent]) × Age group (younger [white bars] vs older [black bars]) interaction. Error bars indicate standard error of the mean associated with repeated measures least-squares means.

incurs a cost to accuracy relative to single task blocks, that is, larger in the older adults than in the younger adults. Although most previous studies on task switching emphasize analysis of the RT, this effect generally comports with previous findings of detrimental effects of age when task switching is necessary (Verhaeghen, 2011; Wasylyshyn, et al., 2011). However, the significance of the encompassing higher order interaction indicates a moderating factor, in this case, response-conflict load. That is, the presence of competing stimulus–response mappings affected the size of the age-group difference in mixing costs. In this case, the age-group difference in switch costs is larger when the two tasks indicate opposing responses (i.e., when they are incongruent). Although an emphasis is typically placed upon age effects on mixing costs, given the pervasive use of bivalent stimuli (which produce congruent and incongruent responses), at least some of the aging effects may stem from response-conflict load in addition to mixing costs.

The second three-way interaction affecting accuracy was an Age group × Episodic load × Response-conflict load effect. The high episodic condition varies the cue-to-task color mapping from block to block, putting greater demands on the episodic buffer to maintain the task set. As was mentioned in the introduction, studies on this specific phenomenon comparing healthy older with younger adults are scant. One study by Verhaeghen and colleagues (1998) suggests age invariance in the episodic buffer component of working memory. Our finding of a significant two-way interaction on accuracy between Age group × Episodic load indicates that this process is less successful in the older adults as compared with younger adults, suggesting otherwise. As with Contextual load, the size of this two-way interaction is moderated by the Response-conflict load. That is, older adults made significantly more errors when both Episodic load and Response-conflict load were high.

As described by Germano and colleagues (2008), the "episodic buffer offers to the working memory model a more comprehensive approach to the multifaceted processes required in new learning" (p. 628). It is possible that the finding of an age effect on episodic load here reflects the fact that this component of Baddeley's model is sensitive to the amount of exposure within the context of new learning. As the color-rule pairing is fixed in low episodic load blocks, participants have more experience with each stimuli color-task pairing. However, in the high episodic load blocks, the cue-to-task color mappings change, reducing the frequency of exposure: on some blocks, cyan letters require a lowercase/uppercase decision, whereas on other blocks, cyan letters require a vowel/consonant decision. Studies parametrically varying the amount of exposure to items requiring episodic buffer-mediated binding could help to untangle this issue.

These data indicate a pervasive influence of age on several disparate aspects of cognitive control function. The finding of an insignificant four-way interaction between Contextual load, Episodic load, Response-conflict load, and Age group but significant three-way interactions between Age group and both Contextual and Episodic load, each moderated by Response-conflict load, suggests that these processes are largely independent in younger adults but are not independent in older adults. Simple effects analyses revealed that both Contextual control and Episodic control are affected by the Response-conflict manipulation in the older adult groups but not in the younger adult group.

The moderating nature of the response-conflict manipulation is consistent with previous findings, which suggest that dysfunction in cognitive control in older adults is directly related to processing motor output (Hartley & Little, 1999; Mayr, 2001) and upregulating cognitive control processes related to resolving response-conflict (Friedman, Nessler, Cycowicz, & Horton, 2009; Nessler, Friedman, Johnson & Bersick, 2007).

Nessler and colleagues (2007), for example, tested healthy older and younger adults using a simple left–right discrimination task requiring congruent and incongruent responses. They found that older and younger adults performed equivalently in low response-conflict conditions—operationalized as congruent trials following an erroneous response and incongruent trials following a correct response—suggesting that conflict detection and monitoring processes are intact in elderly participants. However, when response-conflict was greatest (on post-error trials requiring an incongruent response), older adults showed higher error rates and increased medial frontal negatives as measured by event-related potentials compared with younger adults. These results suggest that older adults have deficits in the ability to upregulate cognitive control processes under high response-conflict load. Mayr (2001), similarly, found that response-conflict (what he calls "full response-set overlap") impacted the performance of older adults in a task-switching experiment that, like our experiment, investigated performance using bivalent stimuli. Our results fit nicely with these two studies, suggesting that declines in the ability to resolve response-conflict may be particularly salient when cognitive demands on other processes, such as contextual and episodic load, are high.

Koechlin and colleagues (2003) reported that contextual and episodic load functions did not interact behaviorally and were nested hierarchically in the LPFC. To our knowledge, there have been no brain imaging studies using a task-switching paradigm that includes response-conflict load as an independent variable. The Stroop paradigm presents one model of age-related congruency effects that may tap a similar mechanism (Stroop, 1935; and see MacLeod, 1991 for a review). In both task-switching paradigms and the Stroop, response-conflict effects are thought to result from the need to both inhibit automatically triggered opposing responses and resolve competition from this simultaneous activation during incongruent, but not congruent, trials (Kane & Engle, 2003). West and Bell (1997) found using electroencephalography that the Stroop produced reliable age-related effects in the anterior attentional system (Petersen & Posner, 2012), including the anterior cingulate cortex and medial and lateral PFC, regions shown to be compromised in older adults (Cohn, Dustman, & Bradford, 1984; Panek, Rush, & Slade, 1984; Spieler, Balota, & Faust, 1996). These effects stem from interference from incongruent trials, as older and younger adults perform equivalently on congruent Stroop trials (Hartley, 1993; West, 1996). Investigations of age-related changes in brain function during the Stroop thus present potential regions of interest to investigate the neural mechanisms driving task-switching response-conflict effects. This focused aspect of task-switching experiments may reveal brain-based age differences. Future imaging work is thus needed to elucidate the response-conflict mechanism and tease apart its interaction with different types of cognitive control in older adults.

The notion of two processes (contextual and episodic load) in series with a third dealing with stimulus–response mapping is broadly consistent with Koechlin and colleagues' (2003) hierarchical model of cognitive control. It is most notable that the inclusion of older participants here allowed a more precise elucidation of the relations among the mechanisms proposed by Koechlin and colleagues than would have been evident in an equivalent analysis excluding the older adults.

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